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INTERNATIONAL SEMINAR ON PELLET-CLAD INTERACTIONS WITH WATER REACTOR FUELS

9-11 March 2004
Aix-en-Provence

English - Or. English

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International Seminar on

PELLET-CLAD INTERACTION IN WATER REACTOR FUELS

organised by
CEA Cadarache/DEN/DEC

in co-operation with
OECD/NEA, IAEA, EDF, FRAMATOME ANP, COGEMA

9 - 11 March 2004

Hôtel NOVOTEL PONT-DE-L'ARC
1 avenue Arc de Meyran
13100 Aix en Provence, France

Introduction

This was the third in a series of three seminars that started with the seminar on « Thermal Performance of High Burn-Up LWR Fuel» at Cadarache, France, 3 to 6 of March 1998, followed by « Fission Gas Behaviour in Water Reactor Fuels», also held at Cadarache, from 26-29 September 2000.

The aim of this third seminar was to draw up a comprehensive picture of our current understanding of pellet clad interaction and its impact on the fuel rod, under the widest possible conditions.

Pellet-Clad Interaction

In PWRs and BWRs, once the fuel-clad gap has closed, 1 to 3 years after irradiation started (depending on the materials), the compressive stress experienced by the cladding and due to the primary fluid pressure is reversed to a tensile stress induced by continued fuel swelling.

Enhanced clad stress is likely to occur in the region of the pellets' ends, especially when the fuel rod is submitted to power ramps, in relation for instance with incidental transients in the operation of the reactor.

In the presence of aggressive fission products (e.g. iodine typically) released by the pellets, this situation can lead to stress corrosion induced failures resulting in primary water contamination.

This risk is an important industrial challenge to demonstrate that margins are guaranteed for the different current situations and for classes of transients encountered in reactors operation, and justifies the development of so-called PCI-resistant fuel products.

Fuel and Pellets Behaviour Mechanisms Activated in PCI Situation

The behaviour of pellets in the interaction depends on many mechanisms potentially activated prior to, or during PCI, namely:

- densification/solid fission products and gaseous swelling under irradiation,
- release of fission gases and volatile species,
- evolution of thermal conductivity, elasticity constants, thermal and irradiation creep, temperature-induced, or microstructure-induced phenomena (porosities, recrystallisation),
- geometry of the pellets and their modifications by cracking.

As to the clad:

- evolution of elasticity, plasticity, creep parameters (irradiation, temperature-induced),
- dependence on the microstructure and manufacturing process and its evolution under fluence,
- oxidation, hydridation,
- sensitivity to stress corrosion-cracking.

As to the interface:

- formation of contact materials or bonding layers: zirconia, uranate compound including fission products,
- friction

PCI Experimental Assessment

- The mechanisms described above can be quantified to a certain extent by specific experiments on fresh and irradiated fuel, permitting the development of specific models.

- Integral experiments, using for instance re-irradiation of fuel at different burn-up and subjected to power ramps in MTRs, are also being currently performed.

- The PIE of such experimental rods allows for ridging measurements, detailed cladding examination, enhances knowledge of the structure of the pellets and of the bonding layer.

This assessment generally emphasizes the following:

- clad cracking occurs parallel to the rod axis, in the region of the pellets' ends, and seems to be in relation to the "wheatsheaf" shape of the pellets gained under the influence of the radial temperature gradient,
- higher burn-up seems to provide an alleviation of PCI in relation to the recrystallisation in the RIM zone,
- MOX fuels seem to behave better than standard UO_2,
- The dishing of the pellets seems to play a role as it allows the fuel to creep axially, thus alleviating the stress induced in the clad at pellet ends.

Manufacturing and Design Remedies to Avoid PCI

The modification of the microstructure of the fuel is one of the possibilities explored for the enhancement of resistance to PCI. Doped pellets with different additives have been developed and tested.

Evolution of the cladding material can also contribute to this resistance.
Other possibilities are currently investigated, by modification of the geometry of the pellets or specific barriers on the inner surface of the clads ("liner" concept for BWRs for example).

PCI and Modelling

There are many incentives to progress on PCI modelling, in order to :

- establish a basis for understanding the phenomena,
- rank their relative importance,
- define relevant experiments,
- justify evolutions of the design,
- allow a credible prediction of PCI onset and demonstration of a safe operation of the fuel in core when validated.

Different thermomechanical solutions are developed throughout the world for PCI assessment. They are very challenging as they concern very complex mechanisms with non-linearities of different types. They require checking against extended data bases in order to support convincing demonstrations.

PROGRAMME

Tuesday, March 9, 2004

07:50 to 08:50 : Registration

08.50 to 12.00 : **SESSION 1 : Opening and Industrial Goals**
Session chair person : - P. MARTIN (CEA/France)

08.50 : **Opening and Welcome**

1. 09.00 : "Effect of PWR Restart Ramp Rate on Pellet Clad Interactions", *Suresh Yagnik (EPRI), Bo Cheng, , Dion Sunderland (Anatech)*
2. 09.30 : "Pellet-Cladding Mechanical Interaction in Boiling Water Reactors", *Michel Billaux (AREVA), Hoju Moon*
3. 10.00 : "PCI-related Constraints on EDF PWRs and Associated Challenges", *S. Beguin (EDF)*

10.30 to 11.00 : Coffee break

4. 11.00 : "Review of Operational Requirements with Respect to PCMI in a VVER and the Corresponding Developments in the TRANSURANUS Code", *Paul Van Uffelen (ITU), K. Lassmann, A. Schubert, J. Van de Laar, Cs. Györi, D. Elenkov, B. Hatala*
5. 11.30 : Invited paper : "PCMI Implications for High-burnup LWR Fuel in RIA", *C. Vitanza (OECD), J.M. Conde Lopez*

12.00 to 16.00 : **SESSION 2.1 : Fuel Material Behaviour in PCI Situation, (1)**
Session chair persons : - L.C. BERNARD (FRAMATOME ANP/France)
- D. BARON (EDF/France)

6. 12.00 : "Physical Models Development For Prediction of Rim-Layer Formation in UO_2 Fuel", *V.V. Likhanskii (SRC RF TRINITI), O.V. Khoruzhii, A.A. Sorokin*

12.30 to 14.00 : Lunch

7. 14.00 : "Microstructure Investigations of As-Irradiated, Annealed, and Power Ramped High Burnup Fuel", *Suresh Yagnik (EPRI), James Anthony Turnbull, Robin A. Gomme*
8. 14.30 : "Effect of Thermal and Mechanical Properties of the DUPIC Fuel on the Pellet Cladding Mechanical Interaction", *Ho Jin RYU (KAERI), Kwon Ho KANG, Chang Je PARK, Joo Whan PARK, Kee Chan SONG, Myung Seung YANG*
9. 15.00 : "Out-of-pile and In-pile Creep Behaviour in MOX Fuel", *L. Caillot(CEA), Virginie Basini, C. Nonon,*
10. 15.30 : "Mechanical Characterization of Irradiated Fuel Materials with Local Ultrasonic Methods", *D. Baron (EDF), D. Laux, G. Despaux*

16.00 to 16.30 : Coffee break

16.30 to 18.30 : **SESSION 2.2 : Fuel Material Behaviour in PCI Situation, (2)**
Session chair persons : - M. BILLAUX (AREVA/USA)
- Y. GUERIN (CEA/France)

11. 16.30 : "Fuel Swelling Importance in PCI Mechanistic Modelling", *V. Ioan Arimescu (AREVA)*
12. 17.00 : "Modelling of a Pellet-Clad Mechanical Interaction in LWR Fuel by Considering Gaseous Swelling", *Jin-Sik Cheon (KAERI), Yang-Hyun Koo, Byung-Ho Lee, Je-Yong Oh, Dong-Seong Sohn*
13. 17.30 : "The Contribution to Fission Gas Swelling to Pellet-clad Interaction", *R.J. White (BNFL), P. Cook, R. Corcoran*
14. 18.00 : "On the Relations between the Fission Gas Behaviour and the Pellet-cladding Mechanical Interaction in LWR Fuel Rods.", *Paul Van Uffelen (ITU), Mikhail Sheindlin, V. Rondinella, Claudio Ronchi*

Wednesday, March 10, 2004

07:30 – 08:30 : Registration

08.30 to 11.30 : **SESSION 3 : Cladding Behaviour Relevant to PCI**
Session chair persons : - S. YAGNIK (EPRI/USA)
- C. LEMAIGNAN (CEA/France)

15. 08.30 : "Pellet-cladding Interaction in VVER Fuel Rods", *A.V. Smirnov, B.A. Kanashov, D.V. Markov, V.A. Ovchinikov, V.S. Polenok and A.A. Ivashchenko (SSC RF RIAR)*
16. 09.00 : "Characterization of Volatile Fission Products, including Iodine, after a Power Ramp", *L. Desgranges (CEA), B. Pasquet, X.Pujol, I. Roure, Th. Blay, J. Lamontagne, Th. Martella, B. Lacroix, O. Comiti, L. Caillot*
17. 09.30 : "Testing and Modelling Iodine-Induced Stress Corrosion Cracking in Stress Relieved Zircaloy-4", *D. Leboulch, L. Fournier, C. Sainte-Catherine(CEA)*

10.00 to 10.30 : Coffee break

18. 10.30 : "Observation of a Duplex Zr-Cs-U-O Bonding Layer in High Power Fuel", *S. Van den Berghe (SCK CEN), A. Leenaers, B. Vos, M. Verwerft, P. Blanpain*
19. 11.00 : "Cladding Liner Surface Effects and PCI", *Gunnar Lysell (Studsvik Nuclear AB), Koji Kitano, David Schrire, Jan-Erik Lindbäck*

11.30 to 17.00 : **SESSION 4 : In Pile Rod Behaviour**
Session chair persons : - W. WIESENACK (OECD Halden/Norway)
- S. LANSIART (CEA/France)

20. --:-- : "PCMI Behaviour of High Burnup BWR & PWR Fuels during Power Ramp Test", *Katsuichiro Kamimura (JNESO) (cancelled)*
21. 11.30 : "Results of WWER High Burn-up Fuel Rods Examinations in Process of and after their Testing in the MIR Reactor under Power Cycling Conditions", *A.V. Bouroukine, G.D. Lyadov, S.V. Lobin, V.A. Ovchinikov (FSUE, SCC RF RIAR), V.V. Novikov, A.V. Medvedev, B.I. Nesterov (FSUE VNIINM)*
22. 14.00 : "Ramp Testing of BNFL MOX Fuel", *M. Barker, P. Cook (BNFL), R. Weston, G. Dassel, C. Walker*

12.30 to 14.00 : Lunch

23. 14.00 : "PCI Behaviour of Chromium Oxide Doped Fuel", *C. Nonon (CEA), J.C. Menard, S. Lansiart, J. Noirot , L. Caillot, S. Martin, GM Decroix, O. Rabouille, C. Delafoy, D. Petitprez,*
24. 14.30 : "PCMI of High Burnup Fuel as Manifested by Different Types of Instrumentation and Measurements in the Halden Reactor Experimental Programme", *W. Wiesenack (OECD Halden), T. Tverberg*
25. 15.00 : "Power Ramping In the Osiris Reactor : Data Base Analysis for Standard UO2 Fuel with Zy-4 Cladding", *C. Mougel (CEA), B. Verhaeghe, C. Verdaux, S. Lansiart, S. Beguin, B. Julien*
26. 15.30 : "Experimental Data on PCI and PCMI within the IFPE Database", *J.A. Turnbull (Consultant) J.C. Killeen, E. Sartori*

16.00 to 16.30 : Coffee break

16.30 to 17.30 : **SESSION 5.1 : Modelling of the Mechanical Interaction between Pellet and Cladding (1)**
Session chair persons : - Ph. GARCIA (CEA/France)
- P. VAN UFFELEN (ITU Germany)

27. 16.30 : "Modelling of the Effect of Oxide Fuel Fracturing on the Mechanical Behaviour of Fuel Rods", *Th. Helfer (CEA), P. Garcia, F. Sidoroff, J-M. Ricaud, D. Plancq, C. Struzik and C. Bernard*
28. 17.00 : "A Cracks and Dishing Evolution Model and PCI-SCC Considerations for Fuel Pellets in a Quasi-Bidimensional Environment", *Armando Carlos Marino (CNEA)*

19:30 – 23:00 : **Dinner (offered by FRAMATOME ANP)**

Thursday, March 11,2004

07:30 – 08:30 : Registration

08.30 to 10.00: **<u>SESSION 5.1</u> (continued) : Modelling of the Mechanical Interaction between Pellet and Cladding (1)**
Session chair persons : - Ph. GARCIA (CEA/France)
- P. VAN UFFELEN (ITU Germany)

29. 08.30 : "Computational Analysis of Nonlinear Structures – Application to MOX Fuel", *<u>S. Roussette</u> (CEA), J-M. Gatt, J-C. Michel*
30. 09.00 : "Mechanical Response of Cladding with a Hydride Lens under PCI Loading Conditions", *<u>Robert Montgomery</u> (ANATECH Corp), Joe Rashid, Robert Dunham - Odelli Ozer, Suresh Yagnik, Rosa Yang*
31. 09.30 : "Assessment of Cladding Relaxation and PCMI Models in INFRA", *<u>Young Min Kim</u> (KAERI), Yong Sik Yang, Dae Ho Kim, Chan Bock Lee, Youn Ho Jung*

10.00 to 10.30 : Coffee break

10.30 to 15.30 : **<u>SESSION 5.2</u> : Modelling of the Mechanical Interaction between Pellet and Cladding (2)**
Session chair persons : - J.A. TURNBULL (Consultant, UK)
- N. WAECKEL (EDF, France)

32. 10.30 : "2D Pellet-cladding Modelling using FEM at NRI Rez plc", *<u>M. Valach</u> (NRI, REZ), J. Zymak et al.*
33. 11.00 : "Modelling 3D Mechanical Phenomena in a 1D Industrial Finite Element Code : Results and Perspectives", *<u>V. Guicheret-Retel</u>, F. Trivaudet, M.L. Boubakar (MARC), R. Masson, Ph. Tevenin (EDF)*
34. 11.30 : "The COPERNIC Mechanical Model and its Application to Doped Fuel", *<u>C. Garnier</u> (Framatome ANP), L.C. Bernard, P. Mailhe, P. Vesco, C. Delafoy, P. Garcia*
35. 12.00 : "Modelling of Thermal-Mechanical Behaviour of High-Burn-up VVER Fuel at Power Transients with Especial Emphasis on Impact of Fission-Gas-Induced Swelling of Fuel Pellets", *<u>V. Novikov</u> (VNIINM), , A. Medvedev, G. Khvostov, S. Bogatyr, V. Kouznetsov, L. Korystin*

12.30 to 14.00 : Lunch

36. 14.00 : "TOUTATIS, an Application of the Cast3M Finite Element Code for PCI Three-dimensional Modelling", *<u>F. Bentejac</u> (CEA), N. Hourdequin*
37. 14.30 : "Methodology for Multi-dimensional Simulation of Power Ramp Tests.", *<u>C. Struzik</u> (CEA), D. Plancq, B. Michel, P. Garcia, C. Nonon*
38. 15.00 : "Modelling of Pellet-Clad Interaction during Power Ramps", *<u>G. Zhou</u> (Westinghouse Electric), J.E. Lindbäck, H.C. Schutte, L.O. Jernkvist, A.R. Massih*

15.30 to 16.00 : Coffee break

16.00 to 17.00 : **PANEL SESSION**

17.00 End of the seminar.

Opening address

by J. Ph. Nabot, head of the Fuel Department at CEA, Cadarache.

It is my pleasure to welcome all of you to this international seminar dedicated to Pellet-Clad Interaction in Water Reactor Fuels. This seminar is the third in a series of three that started in 1998 on the thermal behaviour of the fuels and continued in 2000 with fission gas behaviour.

As you know, this seminar will be devoted to Pellet-Clad Interaction.

It is organized by the Commissariat à l'Energie Atomique in co-operation with the Nuclear Energy Agency (OECD/NEA) and the International Atomic Energy Agency (IAEA). Electricité de France, Framatome ANP and Cogema participated also to the organization of the seminar and to its funding.

It will last three days: Tuesday, Wednesday and Thursday of this week. On Friday, I will be pleased to welcome those of you who declared interested, for a visit at the hot labs at Cadarache, in the Fuel Studies department.

The number of participants: around one hundred and forty, more than fifty from foreign countries, the number of papers: thirty eight, seems to confirm the strong interest in the PCI studies.

The presentations have been organized in five sessions:

In the first one we shall try to introduce the subject in relation to industrial challenges or at least nuclear operators constraints due to PCI. To this aim, we shall have a look at PCI related issues as they appear for different types of water reactors: PWRs, BWRs, WWER.

The second and third sessions will be devoted to materials behaviour: either pellets or claddings including stress corrosion. This will be also the opportunity to discuss the improvements of these materials, the so-called remedies products, especially with the aim at reducing the risks in PCI situations.

Session four will deal with PCI as assessed by in pile experiments, which is of course a very important topic in relation to data bases allowing for well controlled conditions especially relevant for models validation.

Modelling will be dealt with in Session Five. We have in fact two big sessions: pellet behaviour and modelling, so that they have been broken in two in the program.

We shall try at the end, during a panel session, to draw some conclusions of the seminar, in terms of R&D items worthwhile to be tackled further for instance, or other kind of perspectives.

This is quite a large program and I have no doubt that its achievement will contribute at least to a clear status of the subject, and hopefully to track solutions for a an improved, safe and more convenient mastering of PCI, with alleviated constraints.

I wish to all of you a good work and a good stay in Aix en Provence and look forward to see those of you attending the visit, at Cadarache.

Instructions by Chairman Philippe Martin

We shall start by a session explaining a little bit the story of PCI, how it was dealt with in the past by specific manoeuvring criteria for instance, with specific post refuelling start-up strategies, by adjustment of linear power and so on, how also there is a kind of race between the improvements relative to PCI concerns and the continuous seek for higher performances of the fuel.

Nuclear operators should tell what the consequences of the remaining constraints are for them and their incentives to alleviate them. We shall have this look at PCI from the standpoint of different types of water reactors, including Candu and eastern countries' VVER.

I must give a few explanations about the reason why this section will also include a paper on Reactivity Injection Accident. In fact the organising committee received quite a number of proposed papers clearly in the scope of RIA and not on class 2 transients. So, it was felt that it was better to have an insight on RIA and decided to invite a paper, that should be as neutral as possible in order to bring some elements on PCMI in a RIA situation and allow for assessing common but also specific issues. We should not go into further details on in RIA during this seminar, and leave this to others at a different meeting.

Session Summaries

SESSION 1 : Industrial Goals
Ph. Martin (CEA/France)

An overview of PCI issues was given from the standpoint of history, as well as of reactor types, constraints on plants operation and assessment methods.

PCI failure occurrence was rather high in the 70's. In the 80's, the number of failures were still observed, especially in BWRs, while some restrictions in reactor operation or specific liner design for clads, based on first assessments, were proposed and applied respectively for P & BWRs.

S. Yagnik presented a PCI assessment method based on the FALCON CODE. Its result is expressed in terms of a time/temperature/stress cumulative damage index, relying on thermal-mechanical analysis on the whole power history of the fuel, and on data of time to failure tests of pressurized clads filled up with iodine and function of stress level, temperature, burnup and material. Preconditioning guidelines, ramp rate restrictions… can be usefully derived on the basis of such an index.

M. Billaux described the situation and its evolution on BWRs, which may be a bit more sensitive to PCI (power changes associated with blades pulls especially, can result in high linear heat generated rate variations – due also to neutronic specificities of BWRs as axial variation of moderation ratio). He commented the performance of remedies like clads with a zirconium layer, but concluded that benefits of improved products and specific restrictions on manoeuvring are in fact in permanent competition with the will to enhance the performances of the fuels. At present the number of failures in BWRs increases again, with no fully clear understanding. He mentioned that liner clads are not considered as a definitive solution to PCI. He also emphasized the importance of QA for pellets, as chipped pellets are clearly a factor favouring PCI failures.

S. Béguin commented how PCI is managed (successfully in the thousand of reactor years accumulated today) in EDF's fifty-eight PWRs to cope with the guarantee asked by the Regulatory Authority to preclude PCI in normal and upset (class 2) transients. The approach relies on a thermal-mechanical criterion, capable of discriminating failure from non-failure on a dedicated ramp program on the fuel product concerned. The knowledge of the power history (neutronics, thermal-mechanics) of each rod is necessary. A costly, time consuming experimental program (necessary for each new product), and a huge amount of calculations are requested. At the end, the plant operating diagram is reduced and extended reduced-power operation times must be monitored by operators (dedicated procedures, credit factor), in some cases be limited, resulting in capacity, load follow-up limitations… These are the reasons why EDF expects a lot about new products, compliant enough with regard to PCI hazard, to cancel all kind of PCI constraint, by the year 2010.

P. Van Uffelen presented how the PCI (and also LOCA) approach was modified in eastern countries when independent regulatory authorities were created in the early 90's and who introduced new QA & requirements prior to fuel loading in the reactors. The ITU fuel code Transuranus is used as a basis for the assessment of these situations but had to be modified to cope with specific design (hexagonal lattice, annular pellets), materials (Zr1%Nb) and safety criteria of VVER. Some limits have been reviewed too: allowable strain for instance, for taking into accounts the speed of the transient incident. Adaptations and their validation were presented. They are based on the Russian work and on experimental programs such as SOFIT, the IFPE database, and the OECD Halden Reactor Program, against which the performances of the code were shown. The work ("EXTRA project") is now directed toward accidental and storage conditions.

The invited paper by C. Vitanza was the opportunity to compare PCMI in a RIA situation and in upset situations. On the basis of the Cabri & NSRR programs, it was shown that RIA-induced PCMI is also governed by fuel expansion due to the power deposit but starts generally from the outside of the clad. The corrosion (outside oxidation and hydriding of the outer rim of the clad) is very important as it determines how brittle the clad is. Temperature effect on the clad is moderated (maximal inside), as time does not allow for hydride dissolution, but affects nevertheless clad ductility (making quite a difference between NSRR and Cabri fractures). Strain rate (width of the pulse) effect is also moderated (but connected, at last, to temperature). In RIA, PCMI is stronger at high burnup due to greater fuel swelling.

As a conclusion of the session, there is no doubt that PCI is still a hot topic with considerable industrial issues, involving more availability and competitiveness of nuclear power, and maybe new fuel products and qualification programs. The R & D on the very complex and non linear, thermal, mechanical, chemical phenomena, with the best equipments and relevant experiments seems worthwhile and justifies fully the dedicated sessions to come. A great merit of these could be to emphasize some highest interest tracks on the basis of the current knowledge.

Session 2.1: Fuel Material Behaviour in PCI Situation (1)
Chair : Louis-Christian BERNARD, Daniel BARON

The first paper, presented by V.V Likhanskii (SRC.RF.TRINITI), deals with the development of a physical model to evaluate the rim-layer formation in UO_2 fuel based on the redistribution of vacancies close to the dislocations, and the increased mobility of gas atoms, with a relation between the Xe effective diffusion coefficient and the vacancy concentration. The rim bubble growth is made easier by the pinning on dislocation intersections. New irradiation induced effects of Xe atoms drift in vacancy concentration gradient and Xe redistribution to the vacancy rich regions of the fuel grain are discussed. The assumption proposed is that the main dislocation source is the grain boundary. As a consequence, the dislocation density in the grain volume is inversely proportional to its average radius. The author explains this way why large initial grains delays fuel restructuring.

The second paper presented by Suresh Yagnik (EPRI) is a compilation of all data acquired in the last past 10 years on the fuel micro-structural transformation on fuel discs specimen and standard fuel pellets. Conclusions are proposed on the gas localisation and grain boundary interlinkage state, depending upon the local operating conditions and local burn-up reached. The consequences on a RIA transient and fuel dispersal risks are discussed. It is concluded that further works conducted to explore more widely the fuel dispersal phenomenon and quantify the energy released as a function of Burn-up, restraint level and heating rates are required.

The third paper presented by Ho Jin Ryu (KAERI) focuses on the effect of the use of DUPIC fuel, with different thermal and mechanical properties, on the rod PCMI behaviour. The Young's modulus is assumed not to vary with burn-up, but only with the porosity. DUPIC fuel has a Young's modulus 5 % higher than standard UO_2, and a creep rate about 50 times lower. It is concluded that a decrease in the fuel thermal conductivity results in a large change of the fuel performance of this fuel design. It is also concluded from statistical sensitivity analysis that the fabrication parameter could be optimised to reduce PCMI failure risk in the DUPIC fuel.

The fourth paper presented by Laurent Caillot (CEA) deals with out-of-pile and in-pile MOX fuel viscoplastic behaviour. The fact that MOX fuel tested under transient conditions behaves particularly well compared to standard UO_2 fuel is discussed. Differences at low burn-up are partly explained by the intrinsic properties of the material, mainly due to the larger primary creep rate and a higher creep rate at low and intermediate stresses. About their amplification at higher burn-up, the micro-structural evolution of the Pu clusters and different oxidation of the fuel are likely to be involved. It is concluded that further data are needed to resolve remaining uncertainties as to the different possible explanations.

The last paper, presented by Daniel Baron (EDF) describes a device based on focalised acoustic techniques which has been developed in the past six years, in order to perform local elastic modulus measurements on fuel pellet cross sections prepared for optical analysis. Firstly the data base shows a predominant effect of the porosity volume fraction and the decrease of the elastic modulus with the accumulation of fission products. A recovery is observed which is likely related to the gaseous fission products mobility during rim formation or operating at high temperature. This device development is part of a larger project in order to acquire the overall mechanical properties evolution in irradiated fuel, both out-of-pile and in-pile. This work has already started with ITU (out-of-pile micro-indentation) and Studsvik (in-pile indentation). However further sponsors would be welcome.

Discussions

The chemical evolution of the fuel material inherent to the local fuel transmutation and local thermal conditions induces an evolution of the fuel material's local properties, both thermal and mechanical. This is obvious for the fuel regions concerned by the High Burn-up Structure transformation, but is true for the rest of the material as well. As soon as irradiation starts, a new equilibrium is established in the material defects, particularly in the Oxygen sub-lattice. Depending upon the local temperature, the total amount of irradiation defects reaches a balance depending upon the thermal recovery.

It is therefore difficult to trust the validity of data properties acquired on fresh fuel material to compute accurately the in pile fuel rod thermo-mechanical behaviour and perform the PCMI 3D calculations. In the past twenty years a large amount of work has been performed on the fuel thermal properties up to 100 GWd/tM (NFIR, HBRP, HRP experiments). The mechanical properties data base is still poor with out of pile Micro-hardness tests (Jose Spino) and the following of cladding deformation on instrumented rods.

Works on HBS transformation and MOX fuel particularities show that further investigations are needed to understand these changing material properties with regard to the PCMI behaviour.

Recommendations

1) More efforts are needed to develop clever devices able to provide data on the evolution of the fuel mechanical properties with local burn-up and temperature.

2) In order to better understand the reason for MOX fuel's good PCMI behaviour, further work is needed.

3) For the case of rapid transients further work has to be carried out to explore more widely the fuel dispersal phenomenon and quantify the energy released as a function of Burn-up, restraint level and heating rates.

SESSION 2.2 : Fuel Material Behaviour in PCI Situation, (2)
M. Billaux (AREVA/USA) and Y. Guerin (CEA/France)

Session 2.2 addressed the interaction between the stress field and the fission gas behaviour in the fuel pellet.

An increase of the linear heat generation rate may induce important stresses in pellet and cladding. At low temperature the stresses mainly result from fuel thermal expansion. But at high temperature the contribution of fuel gaseous swelling becomes significant. In order to determine the severity of Pellet Cladding Mechanical Interaction (PCMI), all modern fuel performance codes take into account gaseous swelling during power increase.

On the other side the stress field in the fuel pellet plays a significant role in the fission gas behaviour. A high hydrostatic stress resulting from PCMI inhibits gaseous swelling by hot pressing of the inter-granular porosity, and therefore also limits fission gas release.

V.I. Arimescu (AREVA, USA) described a mechanistic gaseous swelling model as well as the multiple interactions between gaseous swelling and the pellet and cladding mechanics. Gaseous swelling is assumed to come from inter-granular bubbles only. The important role of gaseous swelling in ramp conditions is illustrated by the calculation of three Mark-BEB PWR fuel rods irradiated to 62 MWd/kgU in Arkansas Unit 1 and subjected to power ramps to peak power levels of 39.5, 42 and 44 kW/m in the Studsvik reactor. The results show that gaseous swelling accounts for as much as half of the permanent cladding diametral deformation.

J.S. Cheon et al (KAERI) described a finite-element model based on ABAQUS to describe the mechanical behaviour of the pellet-cladding system. The model is linked with the fuel performance code COSMOS that also includes an integrated fission gas release and gaseous swelling model. The effect of the hydrostatic pressure on gaseous swelling is taken into account, as well as the influence of the friction factor between pellet and cladding. The PCMI model was verified by calculating a PWR MOX rod irradiated to 25 MWd/kgMOX and subjected to five successive power ramps at increasing ramp terminal levels. Each ramp has been followed by a relaxation period of about 24 hours at ramp terminal level (phases 1 to 5). By switching on and off the gaseous swelling model it is demonstrated that the contribution of gaseous swelling on the cladding elongation is small at low power (phase 1), but significant at high power level (phase 5).

For R.J. White (BNFL) the principal driving force for PCI is provided by the two components of gaseous swelling: the intra-granular and inter-granular bubbles. During power transients the finely distributed intra-granular porosity increases with a faster kinetics than the coarse inter-granular porosity. Both processes are constrained by the effect of irradiation induced re-solution. This is illustrated by the comparison between the swelling behaviours of two AGR rods base irradiated to burnups of 12-15 GWd/tU and ramped in the

Halden reactor. Both rods were subjected to slow ramps in which the power increased over a period of 45 minutes. One was followed by two fast ramps and then discharged. The other one was maintained at low power for an additional 28 days prior to discharge. Extensive SEM analysis was performed that showed that both intra-granular and inter-granular swelling significantly decrease during the extended period at low power. An irradiation induced re-solution mechanism is proposed to explain that reduction.

P. Van Uffelen (ITU) et al made a review of the in-pile and out-of-pile tests reported in the literature describing the effect of the stress distribution in the pellet on fission gas release and gaseous swelling. This was followed by a second literature review assessing the validity of various pellet mechanical models and the use of the hydrostatic stress in the gaseous swelling models. They underline the imperfect modelling of the stress distribution in cracked pellets that would require a 3 D modelling of the pellet, as well as the limited amount of reliable experimental data. A new experimental device is being developed at ITU that will bring complementary information on the interaction between the fission gas behaviour and the stress distribution in the pellets. One of the proposed experiments consists in analysing the effect of hydrostatic stress via a variable helium pressure, in combination with a variable temperature level in a high burnup fuel rod segment.

In conclusion, two points seem well established:

- Gaseous swelling has a significant impact on PCI. Fuel failures usually arise only through the additional strains produced by fuel gaseous swelling.
- The stress distribution in the pellet has an important effect on fission gas release and swelling.

There is, however, a need for improvement in the following fields:

- The relative importance of intra-granular swelling is still subject to controversy.
- Reliable experimental data are needed to better characterize fuel gaseous swelling (including irradiation induced gas atom resolution) in different conditions of temperature, stress and fission rate.
- Despite considerable improvements of the pellet mechanical modelling in the last decade, efforts should be pursued. A better characterization of the local stress (stress tensor against hydrostatic pressure) might be necessary for a comprehensive modelling of the different ways stresses affect the fission gas behaviour. Multidimensional mechanical models might help.

It is also recommended to revisit the existing fuel performance databases and re-analyse them focussing on gaseous swelling.

Gaseous swelling is likely to be a major field of development in the next years.

SESSION 3 : Cladding Behaviour Relevant to PCI
S. Yagnik (EPRI/USA) and C. Lemaignan (CEA/France)

This session had five excellent papers on experimental observations regarding PCI behaviour.

The first paper was about PCI behaviour in VVER fuel rods. It presented up to 5 cycles PIE data. The key conclusion was that with large as-fabricated gap, reported cladding strains (maximum ~ 0.3%) are still well below allowable limit of 0.4% even at high burn-ups. Further, since VVER fuel behaviour under transient condition was also the subject of two additional papers in the Seminar, collectively these papers will certainly prove useful in modelling and validating predictions of VVER fuel behaviour.

The second paper provided interesting observations concerning volatile fission products after a power ramp, using SIMS and X-ray mapping techniques. Results showed that Cs and I are not necessarily colocated in the fuel. While some CsI was observed, there was clear evidence of free Cs and I as well. An important question was about the role of Cd., which could be pursued in the future using these techniques.

The third paper on testing and modelling of I-SCC phenomenon presented useful data on hoop strain vs. failure times in iodine environment on un-irradiated and irradiated tubing samples. The two types of samples behaved very differently. It was noted that the texture effects are important, especially for un-irradiated samples. Such data, especially on newer cladding materials, are requisite inputs for deterministic modelling of PCI failures. The paper presented a failure model based on the data. But other modelling alternatives, e.g. cumulative damage index, could also benefit from these data.

The fourth paper documented important observation about pellet-clad bonding layer. Complex triplex layers were found to exist in the fuel, especially and somewhat randomly, within fuel pellet cracks and at pellet-pellet interfaces. The fuel examined was un-ramped fuel of modest burn-ups. Fuel oxygen potential appears to be an important variable in dictating the nature and composition of bonding layer compounds. The main question still is how this bonding layer changes the gap conductance and what role does it play in localized stresses on the cladding that may trigger PCI phenomenon.

The final paper was on micro-hardness measurements of a BWR cladding ID barrier layer. It was noted that fission fragments impinging on the clad ID tend to increase local hardness within about 10 µm, which is the expected range of fission fragments. Micro-hardness measurement technique could provide insights into how clad properties change with burn-up. When employed on samples from sound and failed BWR rods with improved liners, this technique is likely to provide important data on secondary fuel degradation phenomenon in BWRs.

SESSION 4 : In Pile Rod Behaviour
W. Wiesenack (OECD Halden/Norway) and S. Lansiart (CEA/France)

Six papers were presented in session 4 devoted to rod in-pile behaviour. They covered different experimental techniques and PIE, different fuel types such as standard and doped UO_2, VVER fuel and MOX fuel, and a range of burnups.

It appears that quite a lot of data are available for understanding PC(M)I.

The IFPE database collects an impressive amount of results from experiments performed over the years for different types of reactors. Modellers were encouraged to make active use of this database and to give feedback to the NEA. Only then can the continued support of this activity be justified and the database even be extended.

The OECD Halden Reactor Project programme gives many answers to the basic questions concerning contact features:

- when does PCMI appear and how does it evolve with increasing burnup (indications obtained from in-pile clad length measurements)?
- when does the fuel-cladding gap more or less close and what about the impact of a tight fuel column on axial gas communication?
- how does the fuel-cladding system respond to overpressure, e.g. does the gap open or do fuel fragments relocate in the case of lift-off ?

It was shown that the VVER fuel has good power cycling capabilities at the burnup level tested (50 - 60 MWd/kg). Progressive relaxation of PCMI strains and a shift of PCMI onset to higher power occurred as the number of cycles increased. Also two successive ramps to high power demonstrated, by way of simultaneous measurement of axial and diametral strain, that the fuel has good ramping capabilities. Absolutely no detrimental effect on the cladding integrity was evident as a consequence of these operation modes.

The results of a ramp testing program were also reported for MOX fuel irradiated in the Beznau reactor to about 30 MWd/kg and then ramped in the Petten MTR. No fuel failure was registered although the failure threshold valid for UO_2 fuel was exceeded. This outcome is another confirmation that MOX fuel is more resilient to failure than UO_2 fuel.

The performance of chromia doped fuel was evaluated in a ramping program using the Osiris MTR. Although the large grains purposely produced by this kind of doping might imply an inferior PCMI behaviour, the contrary was demonstrated by this experimental program. No failure was observed, which may be explained by the enhanced visco-plasticity of the fuel as well as the development of a favourable crack pattern with numerous radial cracks on the pellet surface mitigating local stress concentrations in the cladding.

Sixteen ramps have been performed on rods with the same PWR design (standard UO_2 fuel with Zy-4 cladding) in the OSIRIS MTR. If failure occurs due to PC(M)I, it is typically an SCC type of fracture at a location close to a radial fuel crack, in the inter-pellet plane. The results show quite deterministic behaviour of these rods. Linear heat rate may be considered as the best experimental parameter available for ranking the 2-cycle rods as regard to the cladding damage extent.

But concerning the central issue of how to prevent PCMI failure while increasing the economics of nuclear plants, many questions are still open. Standard UO_2 fuel with Zy-4 cladding leads to constraints in plant operation. MOX fuel and Cr-doped fuel appear very promising, but the reason why they work as PCI remedies is not clearly evident. Is it fuel cracking propensity by itself, is it enhanced viscosity reducing the hour-glass effect by dish filling and perhaps favouring peripheral cracking? How does gaseous swelling act, with which kinetics?

These questions might be answered by predictive numerical simulation if we were able to perfectly model all the fuel properties under irradiation conditions. But in a real world with imperfect knowledge, this is not the case - especially when the effects of high power ratings must be considered. So there is a need for new experiments in which the contribution of some phenomena is reduced as much as possible. That is the case for gaseous swelling for the zero hold time ramp test which has been proposed on Cr-doped fuel. It would be the case for gaseous swelling plus creep at higher ramp rates.

Relevant comparative analytical data with differences in pellet geometry (e.g. short pellets) could contribute as well to this attempt of varying the relative weight of different phenomena.

Finally, the question of the concurrent cladding improvement might be asked. Despite the fact that the liner concept is more or less abandoned for BWRs due to its possible degradation, the question is whether it is unreasonable to expect benefits from a new cladding concept as well.

SESSION 5.1 : Modelling of the Mechanical Interaction between Pellet and Cladding (1)
Ph. Garcia (CEA/France) and P. Van Uffelen (ITU Germany)

From the review of experimental data obtained in the OSIRIS reactor, it was concluded that the risk of I-SCC is greatest at the pellet interfaces. In line with this, in session 5.1 people naturally resort to *multidimensional modelling* in order to describe the specific state of the strain/stress state of the cladding. Furthermore, fuel *fracturing* appears to have significant consequences on the behaviour of oxide fuel, in particular on PCMI. This also transpires from the experimental data presented in session 4 on Cr-*doped fuel* where the question arose as to whether creep or cracking could account for the improved PCI resistance.

With the introduction of mixed oxide fuels in LWRs as well as the increase of the fuel assembly discharge burnup in UO2 fuel, there is a need to account for the *heterogeneous* and/or porous microstructure in the thermomechanical analysis of fuel rods. In this respect, paper 29 describes a novel way of generating visco-plastic fuel behaviour laws for heterogeneous fuels (MOX, IMF, etc.) based on the knowledge of its macroscopic behaviour, its microstructure and on the behaviour of one of the phases.

In design basis accident conditions, the multidimensional approach also turned out to be necessary to improve the assessment of the critical conditions for *hydrided cladding* failure. As a corollary to this analysis, it was pointed out that one should be careful when applying the results from out-of-pile burst tests to in-pile conditions because of the differences between *pressure driven and displacement driven cladding deformation*. Finally, the friction between cladding and fuel was also shown to play a significant role in quantitative analyses in all operating conditions, although very different values are being applied.

Perspectives for model development that have emerged from this session include *de-cohesive models* as an alternative for diffusive crack models to reach a more physical fuel cracking description, and the *Non-uniform Transformation Field Analysis* to account for the heterogeneity in some nuclear fuels.

SESSION 5.2 : Modelling of the Mechanical Interaction between Pellet and Cladding (2)
J.A. Turnbull (Consultant, UK) and N. Waeckel (EDF, France)

There were seven papers in this session devoted to modelling the mechanical interaction between fuel and cladding. In the period between FUMEX-I and the present meeting, it was good to see the interest and progress made in addressing this topic.

The focus of fuel modelling has progressed from thermal performance and fission gas release (FGR) to Pellet Clad Mechanical Interaction (PCMI). Whereas there has been a common approach to thermal performance and FGR involving 1D/1.5D codes, there has been a divergence in approach when moving forward to mechanical interaction involving either 1D/1.5D or 3D codes. Time will tell which is the more successful, however, for applications where many calculations need to be performed 'on-line' with reactor operation, there is a clear need for the faster running 1D/1.5D codes possibly with input from the slower running 3D codes in order to provide "fixes" for more simple models of the PCMI phenomenon.

Many papers concentrated on the behaviour of the pellet, with little attention paid to modern cladding with their improved properties[1]. This is understandable as the driving force is thermal expansion and swelling of

[1] The different types of cladding can be easily differentiated in term of mechanical properties or in-reactor corrosion performance but in terms of sensitivity to SCC, separate effect tests are not yet capable of discriminating an alloy A from an alloy B. If we assume that the amount of fission products necessary to initiate a SCC crack is always available, one can conclude that it is more relevant to focus on investigating the driving forces (i.e. the pellet induced stresses to the cladding) that can be different from one type of pellet to another one.

the pellet. As gaseous swelling is the most onerous contribution to clad strain, it is well to concentrate on this phenomenon. Papers presented in other sessions indicated that there was much data available on this topic, and modellers were urged to use these data extensively in their development and validation of their PCMI models, concentrating in the first instance on predictions of clad diameter change and ridge height growth during periods of transient over power. Additional attention was required in modelling fuel cracking and its consequence, pellet-clad friction coefficient and pellet creep. Regarding the friction coefficient, there was a large variation in the values chosen in the papers presented.

At present the codes are in a development phase with limited testing against experimental data. The ultimate goal of these codes is the prediction of failure probability and this was a future stage in the development of most codes. Again, there were much data openly available from ramp tests in which failure thresholds had been identified for both PWR and BWR systems. It was stressed that for accurate predictions of failure, a large database was required to maximize statistics between failure and non-failure. In addition, it was clear that there was a difference in behaviour between standard UO_2, UO_2 with additives and MOX. It was necessary to explore these differences and understand why the fuels behaved differently. In this way, further improvements in PCI resistant products was possible. Such a programme including both modelling and experimental approaches was necessary to achieve the goal of a "zero failure policy", where failure by PCI did not occur and hence was no longer a safety issue.

PANEL Summary: C. Lemaignan (CEA/France)
Towards a PCI Free Fuel!

After a very fruitful meeting during which the contributions were numerous and the discussions have been intense, a few general and/or prospective comments could be proposed. Since all session chairmen have made detailed and accurate reports on the major issues of each session, the purposes of the following comments are manly to stress interactions between the different aspects presented and to highlight a few points of potential concern or scientific interest.

The three main parameters controlling the failure during a PCI event are the stress distribution, the internal chemistry close to the inner surface of the cladding and the material properties. It should not be forgotten that the fuel rod acts as a system and that these different contributions interact with each others. The meeting has been a very good opportunity to stress this point and the development of thermo-mechanical computer codes, aiming at the integration of the fuel rod system, clearly contributes to such approach. The corresponding modelling procedures are used for a better knowledge of the interacting processes. They are benchmarked with several analytical or global experiments and are developed with an expected capability of forecasting the potential failure of a rod, or the margins for a specific operational condition.

With respect to the **mechanical stress state**, the interaction between oxide and cladding requires its computation in the two materials with similar accuracy. However, the stress state is not a scalar, but is defined by a tensor. Also the definition of the stresses can be performed at different scales. For crack initiation, it should be analyzed almost at the grain scale, while the analysis of the failure risk of the rods in a core would clearly require a much larger mesh. A critical point is therefore the procedures used for the reduction and condensation of the detailed analysis to the macroscopic scale.

Among the major points risen during the meeting, the large contribution of the gas bubble swelling during a power transient to the stress development in the cladding has been confirmed. The total strain induced by the gas bubble precipitation and fuel swelling has been measured in a very few cases; however, the detailed kinetics of this swelling, for given BU, temperature and hydrostatic stress state histories, is still practically unknown. Due to the viscoelastic behaviour of the oxide and of the cladding, the exact knowledge of the kinetics of this swelling will be a critical parameter. Experiments on fuel rod transients during which the local diameter strain is measured continuously are strongly recommended with respect to this point.

The significant progresses made in thermomechanical computations should also not be damped by using a set of physical properties of the materials of low accuracy. The quality of the computations will never deliver results of better value than those limited by the data. This supports the interest for a reassessment of them as described below. This progress also induces a strong requirement for a much finer definition of the boundary conditions (small changes in the geometry of the fuel rod have been shown to affect severely the local stress state…)

The impact of **chemistry** induced by fission products on the PCI failure is not questionable. It remains, however, that the exact state of the fuel inside the rod is still far from being clearly described. The moderate temperature of the fuel during normal operation is not high enough for obtaining phase equilibrium as expected form thermodynamics. However for high BU fuel, the driving force for such equilibrium is highly increased and observations confirm the existence of phases not observed at lower BU. Due to the observed mitigation of the I-SCC by oxygen, and possibly other species, a better knowledge of the actual chemistry would allow major progress in understanding the PCI mechanisms. With respect to this, the apparent improvement in PCI resistance observed for high BU, Cr-doped or MOX fuel could be due not only to the better viscoplasticity of the fuel, but possibly to an unexpected chemical phenomenon. Detail observations of the phases present in the rod, and specifically in the fuel-cladding gap, would be useful for a better modelling of the chemical environment of the stressed cladding.

For the **material properties**, most of them are usually considered as known since a long time. However, as the irradiation is known to significantly affect the physical properties of the fuel rod materials, progress is required for their definition in order to maintain at parity computation techniques and physical property data. This will specifically concern thermoelastic properties (Young's modulus, thermal expansion coefficient, heat conductivity and the kinetics of their evolutions during thermal recovery…) as well as the mechanical properties (yield strength, creep behaviour…). In addition, some properties may have a very different meaning if the conditions of use are different from those of data acquisition. This would be specifically the case for plastic strain behaviour of irradiated Zr alloys. In the case of such a strain softening material, the loading scheme drastically affects the behaviour: pressure tests are load controlled and will lead to local instability and very limited total strain to failure, while PCI loading is a local stain controlled loading procedure. The local reduction of strength induced by the strain does not produce local instability.

For the **future**, the scientific community concerned with the analysis of the behaviour of the fuel should probably follow more closely what is under promising development in the field of material science: the computational material science. Due the difficulties and costs in testing materials (including power ramping) and performing very fine examinations on irradiated materials, the rising science of knowledge of the materials as deduced form computations, is a major challenge for the forthcoming years. For the fuel rod chemistry and the reaction at the crack tip in the cladding, quantum chemistry and mesoscopic approaches seem to be appropriate tools for interatomic interaction description. For the irradiation point defects evolution, and their impact on microstructure, molecular dynamics or kinetic Monte-Carlo will allow, in a close future, to forecast fission gas bubble nucleation and growth or creep properties of UO_2 or other doped oxides.

These techniques should not forget the large data bases acquired in the early days of the nuclear industry. If detailed experimental conditions are not always reported, a mine of highly valuable scientific results is laying in the drawers of our predecessors. A good use of them would require a continuous feedback on their usability. The power ramp data collected by the NEA is a significant step towards the revitalization of such old works. Similarly thermodynamics had its glory a few decades ago: it now receives much less consideration.

At the end of this meeting one could expect a significant reduction of the PCI constrains imposed to the utilities in the forthcoming years, either by reduction of the susceptibility of the fuel rods to such failure mechanisms, or by reduction of the power manoeuvrings responsible for PCI. Would therefore such studies be useless, in the possible context of reduction of PCI frequency? Without being pessimistic, the history of the nuclear industry has shown us that unexpected behaviours are ready to occur when pushing the components to a higher duty, a longer life or reduced operational margins. A scientific knowledge of the fuel behaviour beyond what is strictly required to avoid any PCI failure, and we are unfortunately far from such a scientific knowledge, will not be a waste of time or money, but will allow us to react more efficiently in case of such events occurring.

Overall Recommendations and Open Questions

Fuel Material Behaviour in PCI Situation

1) More efforts are needed to develop "clever" devices able to provide data on the evolution of fuel mechanical properties with local burn-up and temperature.
2) Reliable experimental data are needed to better characterize fuel gaseous swelling kinetics (including irradiation induced gas atom re-solution) under different conditions of temperature, stress and fission rate, including the relative importance of intra-granular swelling. Attention should be paid to evaluating the gaseous swelling driving force and its contribution to the local mechanical loading of the clad.
3) Despite considerable improvements of the pellet mechanical modelling in the last decade, further improvements are required. A better characterization of the local stress (stress tensor against hydrostatic pressure) might be necessary for the comprehensive modelling of the different ways stress affects the pellet progressive additional cracking, the viscoplastic flow and the fission gas behaviour. This may necessitate 3D mechanical modelling.

Cladding Behaviour Relevant to PCI

1) Stress corrosion cracking, especially in iodine atmosphere, is known to be responsible for PCI failures. Despite many efforts and good analytical work, the need still exists for developing mechanistic models able to reproduce the mechanical tests performed on pressurized tubes as well as to predict the clad crack propagation in true transient conditions. Knowing that the SCC cracks preferentially develop at the pellet-pellet interface and in front of pellet cracks the need for developing duly validated 3D models becomes clear.
2) In order to better simulate potential clad damage due to power transients, further work is also recommended concerning the migration of potentially aggressive chemical species such as I, Cs, Cd. Since the papers presented in this session focused on the behaviour of I and, to a lesser extent, that of Cs, it is recommended that the experimental efforts be now directed toward understanding the role of Cd.
3) It is recommended that microhardness measurements be pursued to better quantify the evolution of microhardness as a function of burn-up. Such data would be useful not only in understanding PCI SCC but also other phenomena such as secondary damage in failed fuel rods.

In Pile Rod Behaviour

1) The reasons why MOX fuel and Cr-doped fuel appear to behave better with respect to conventional UO_2 under PCI conditions must be tackled further: is it fuel cracking propensity by itself, and/or is it enhanced viscosity reducing the hour-glass effect by dish filling and perhaps favouring peripheral cracking? How does gaseous swelling act, with which kinetics? So there is a need for new experiments in which the contribution of the individual phenomena is evidenced . That is the case for gaseous swelling for zero hold-time ramp tests which have been proposed on Cr-doped fuel. It would be the case for gaseous swelling plus creep at higher ramp rates. In parallel, there is a need for experiments to study the high temperature phenomena not far from fusion conditions without any cladding damage (columnar grain growth, central void formation, etc.).
2) Relevant comparative analytical data with differences in pellet geometry (e.g. short pellets) could contribute as well to this attempt of varying the relative weight of different phenomena.
3) The question of the concurrent cladding improvement might be asked. What kind of benefit can be expected from a new cladding concept?

Modelling of the Mechanical Interaction between Pellet and Cladding

1) The development of de-cohesive models versus diffuse crack models looks promising for the treatment of pellet cracking.
2) Mechanical phenomena are assessed differently by 1D/1.5D and 3D models, only the latter having the potential to approach the phenomenon with accuracy. Nevertheless, running times are long and the results are still dependent on materials data and interaction prediction. So, it seems that both models should be developed, fast-running 1D/1.5D models taking profit of the comprehensive view available from 3D ones
3) The developments on pellets mechanical models to cope with cracking, and the provision of an accurate description of heterogeneous products, should be used as inputs of PCMI codes and could help to understand the differences exhibited by doped fuels and MOX
4) The ultimate goal of all fuel vendors should be a failure free operation, with no limits imposed on operation. PCI resistant products could contribute (see above), but their good performances have to be demonstrated more widely, by modelling and by complementary experiments.
5) It is recommended to extend the use the existing fuel performance databases (e.g. IFPE) for model improvement and validation, and in particular to evaluate PCMI effects on gaseous swelling and vice versa. A FUMEX-III exercise devoted to PCMI/PCI effects should be considered.
6) Predictive PCI modelling should be presented, not just explanations after the event.

List of Participants

The seminar was attended by 140 participants from 20 countries representing 46 different organisations including research laboratories, fuel vendors, NPP operators, nuclear safety institutions and consultancy firms. In all 36 papers were presented plus one invited paper concerning RIA conditions.

Name	Address	Country
MARINO Armando Carlos	Centro Atómico Bariloche Comisión Nacional de Energía Atómica División DAEE 8400 Bariloche	Argentina
KILLEEN John	IAEA, Wagramer Strasse 5, P.O. Box 100, 1400 VIENNA	Austria
HOLLASKY Nadine	AVN, Rue Walcourt 148, 107 BRUSSELS	Belgium
FERNANDEZ Javier	BELGONUCLEAIRE, Avenue Ariane 4, 1200 Brussels	Belgium
BAIRIOT Hubert	FEX, Lysterdreaf 20, B2400 MOL	Belgium
SOBOLEV Vitali	SCK-CEN, Boeretang 200, B-2400 MOL	Belgium
VAN DEN BERGHE Sven	SCK-CEN, Boeretang 200, B-2400 MOL	Belgium
DALLEUR Jean-Paul	TRACTEBEL, Avenue Ariane 7, 1200 Brussels	Belgium
MANDEV Ivatz	Institute for Nuclear Research & Nuclear Energy, BAS, 72, Tzarigradkso Chaussée, 1784 SOFIA	Bulgaria
TAYAL Mukesh	Atomic Energy of Canada Limited, SP2F4 Sheridan Park Research Community 2251 Speakman Drive Mississauga Ontario L5K 1B2	Canada
BELOVSKY Ladislav	ALIAS Cz s.r.o, Bachova 1586/16, 14900 PRAHA 415	Czech Republic
NOVOTNY Michal	Department of Nuclear Reactor Technology, Nuclear Research Institute plc, 250688 HUSINEC-Rer 130	Czech Republic
STECH Svatobor	NPP Dukovany, 675 50 DUKOVANY	Czech Republic
VALACH Mojmir	Nuclear Research Institute Rez plc, Department of Reactor Technology, 25068 Husinec REZ 130	Czech Republic
ZYMAK Jiri	Nuclear Research Institute Rez plc, Department of Reactor Technology, 25068 Husinec REZ 130	Czech Republic
KELPPE Seppo	VTT Processes, P.O. Box 1604, FI-02044 VTT	Finland
CHANTOIN Pierre	Consultant, 232 Impasse du Haut Colombier, 04100 MANOSQUE	France
KALLEND Marie-Claire	CEA/Cadarache, 13108 SAINT-PAUL-LEZ-DURANCE CEDEX	France
ROUSSETTE Sophie	CEA/Cadarache, 13108 SAINT-PAUL-LEZ-DURANCE CEDEX	France
GUERIN Yannick	CEA/Cadarache, DEC, 13108 SAINT-PAUL-LEZ-DURANCE CEDEX	France
MARTIN Philippe	CEA/Cadarache, DEC/DIR, Bldg. 315, 13108 SAINT-PAUL-LEZ-DURANCE CEDEX	France

NABOT Jean-Philippe	CEA/Cadarache, DEC/DIR, Bldg. 352, 13108 SAINT-PAUL-LEZ-DURANCE CEDEX	France
AUBRUN Isabelle	CEA/Cadarache, DEC/S3C/LECMI, Bldg. 316, 13108 SAINT-PAUL-LEZ-DURANCE CEDEX	France
CAILLOT Laurent	CEA/Cadarache, DEC/S3C/LECMI, Bldg. 316, 13108 SAINT-PAUL-LEZ-DURANCE CEDEX	France
DESGRANGES Lionel	CEA/Cadarache, DEC/S3C/LECMI, Bldg. 316, 13108 SAINT-PAUL-LEZ-DURANCE CEDEX	France
NOIROT Jean	CEA/Cadarache, DEC/S3C/LECMI, Bldg. 316, 13108 SAINT-PAUL-LEZ-DURANCE CEDEX	France
DUCROS Gérard	CEA/Cadarache, DEC/SA3C/, Bldg 315, 13108 SAINT6PAUL-LEZ-DURANCE CEDEX	France
PONTILLON Yves	CEA/Cadarache, DEC/SA3C/, Bldg 315, 13108 SAINT6PAUL-LEZ-DURANCE CEDEX	France
BRUNEL Laurence	CEA/Cadarache, DEC/SESC, Bldg. 151, 13108 SAINT-PAUL-LEZ-DURANCE CEDEX	France
PELLETIER Michel	CEA/Cadarache, DEC/SESC, Bldg. 315, 13108 SAINT-PAUL-LEZ-DURANCE CEDEX	France
ANSELMET-VITIELLO Marie-Christine	CEA/Cadarache, DEC/SESC/LIPA, Bldg. 151, 13108 SAINT-PAUL-LEZ-DURANCE CEDEX	France
BAUER Mireille	CEA/Cadarache, DEC/SESC/LIPA, Bldg. 151, 13108 SAINT-PAUL-LEZ-DURANCE CEDEX	France
DUBOIS Sylvie	CEA/Cadarache, DEC/SESC/LIPA, Bldg. 151, 13108 SAINT-PAUL-LEZ-DURANCE CEDEX	France
FAURE-GEORS Hélène	CEA/Cadarache, DEC/SESC/LIPA, Bldg. 151, 13108 SAINT-PAUL-LEZ-DURANCE CEDEX	France
HUET François	CEA/Cadarache, DEC/SESC/LIPA, Bldg. 151, 13108 SAINT-PAUL-LEZ-DURANCE CEDEX	France
LAMBERT Thierry	CEA/Cadarache, DEC/SESC/LIPA, Bldg. 151, 13108 SAINT-PAUL-LEZ-DURANCE CEDEX	France
MENUT Patrick	CEA/Cadarache, DEC/SESC/LIPA, Bldg. 315, 13108 SAINT-PAUL-LEZ-DURANCE CEDEX	France
NONON Chrystelle	CEA/Cadarache, DEC/SESC/LIPA, Bldg. 315, 13108 SAINT-PAUL-LEZ-DURANCE CEDEX	France
GATT Jean-Marie	CEA/Cadarache, DEC/SESC/LLCC Bldg. 151, 13108 SAINT-PAUL-LEZ-DURANCE CEDEX	France
CASTELIER Etienne	CEA/Cadarache, DEC/SESC/LLCC, 13108 SAINT-PAUL-LEZ-DURANCE CEDEX	France
GARCIA Philippe	CEA/Cadarache, DEC/SESC/LLCC, Bldg. 151, 13108 SAINT-PAUL-LEZ-DURANCE CEDEX	France
HELFER Thomas	CEA/Cadarache, DEC/SESC/LLCC, Bldg. 151, 13108 SAINT-PAUL-LEZ-DURANCE CEDEX	France
PIRON Jean-Paul	CEA/Cadarache, DEC/SESC/LLCC, Bldg. 151, 13108 SAINT-PAUL-LEZ-DURANCE CEDEX	France
VALOT Carole	CEA/Cadarache, DEC/SESC/LLCC, Bldg. 151, 13108 SAINT-PAUL-LEZ-DURANCE CEDEX	France
BOULORE Antoine	CEA/Cadarache, DEC/SESC/LSC, Bldg. 151, 13108 SAINT-PAUL-LEZ-DURANCE CEDEX	France

MAILLARD Serge	CEA/Cadarache, DEC/SESC/LSC, Bldg. 151, 13108 SAINT-PAUL-LEZ-DURANCE CEDEX	France
MICHEL Bruno	CEA/Cadarache, DEC/SESC/LSC, Bldg. 151, 13108 SAINT-PAUL-LEZ-DURANCE CEDEX	France
OBRY Patrick	CEA/Cadarache, DEC/SESC/LSC, Bldg. 151, 13108 SAINT-PAUL-LEZ-DURANCE CEDEX	France
PLANCQ David	CEA/Cadarache, DEC/SESC/LSC, Bldg. 151, 13108 SAINT-PAUL-LEZ-DURANCE CEDEX	France
RICAUD Jean-Marc	CEA/Cadarache, DEC/SESC/LSC, Bldg. 151, 13108 SAINT-PAUL-LEZ-DURANCE CEDEX	France
STRUZIK Christine	CEA/Cadarache, DEC/SESC/LSC, Bldg. 151, 13108 SAINT-PAUL-LEZ-DURANCE CEDEX	France
THOUVENIN Gilles	CEA/Cadarache, DEC/SESC/LSC, Bldg. 151, 13108 SAINT-PAUL-LEZ-DURANCE CEDEX	France
LANSIART Sylvie	CEA/Cadarache, DEN/DEC/SESC, Bldg. 151, 13108 SAINT-PAUL-LEZ-DURANCE CEDEX	France
LE FUR Brigitte	CEA/Cadarache, DEN/DIR/AFF-INT, Bldg. 101, 13108 SAINT-PAUL-LEZ-DIRANCE CEDEX	France
LEMAIGNAN Clément	CEA/Grenoble, DEC/DEC/DIR, 17 Rue des Martyrs, 38054 GRENOBLE CEDEX 9	France
MOUGEL Caroline	CEA/Saclay, SEMI/LM2E, Bld. 604, 91191 GIF-SUR-YVETTE CEDEX	France
DEHAUDT Philippe	CEA/Saclay, DEN/DSNI, Bldg 121, 91191 Gif-sur-Yvette cédex	France
FORGERON Thierry	CEA/Saclay, DEN/DSNI, Bldg 121, 91191 Gif-sur-Yvette cédex	France
GUILLET Jean-Luc	CEA/Saclay, DEN/DSNI, Bldg 121, 91191 Gif-sur-Yvette cédex	France
HUMBERT Jean-Marc	CEA/Saclay, DEN/SAC/DM2S/SEMT, 91191 GIF-SUR-YVETTE CEDEX	France
BENTEJAC Fabrice	CEA/Saclay, DEN/SAC/DM2S/SEMT/LM2S, 91191 GIF-SUR-YVETTE CEDEX	France
HOURDEQUIN Nicolas	CEA/Saclay, DEN/SAC/DM2S/SEMT/M2S, 91191 GIF-SUR-YVETTE CEDEX	France
SAINTE-CATHERINE Claude	CEA/Saclay, DEN/SAC/DMN/SEMI/LCMI, 91191 GIF-SUR-YVETTE CEDEX	France
STRUB Claude	CEA/Saclay, DM2S/SEMT 625, 91191 GIF-SUR-YVETTE CEDEX	France
FOURNIER Lionel	CEA/Saclay, DMN/SEMI/LCMI, Bldg. 625, 91191 GIF-SUR-YVETTE CEDEX	France
LE BOULCH David	CEA/Saclay, DMN/SEMI/LCMI, Bldg. 625, 91191 GIF-SUR-YVETTE CEDEX	France
VERDEAU Caroline	CEA/Saclay, DMN/SEMI/LM2, Bldg. 625, 91191 GIF-SUR-YVETTE CEDEX	France

CASTELLI Régis	COGEMA-BUR, BP 94216, 30204 Bagnols-sur-Cèze Cédex	France
CHIARELLI Gérard	COGEMA-BUR, BP 94216, 30204 Bagnols-sur-Cèze Cédex	France
BARON Daniel	EDF/R&D, CEA/Cadarache, DEC/SESC, 13108 SAINT-PAUL-LEZ-DURANCE CEDEX	France
MASSON Renaud	EDF/R&D, CEA/Cadarache, DEC/SESC, 13108 SAINT-PAUL-LEZ-DURANCE CEDEX	France
BEGUIN Stephane	EDF/SEPTEN, 12-14 Ave Dutrievoz, 69628 Villeurbanne Cedex	France
BIZ Sophie	EDF/SEPTEN, 12-14 Ave Dutrievoz, 69628 Villeurbanne Cedex	France
COUTY Jean-Christophe	EDF/SEPTEN, 12-14 Ave Dutrievoz, 69628 Villeurbanne Cedex	France
DELHAYE Benoît	EDF/SEPTEN, 12-14 Ave Dutrievoz, 69628 Villeurbanne Cedex	France
PETITPREZ Benoît	EDF/SEPTEN, 12-14 Ave Dutrievoz, 69628 Villeurbanne Cedex	France
WAECKEL Nicolas	EDF/SEPTEN, 12-14 Ave Dutrievoz, 69628 Villeurbanne Cedex	France
WEISS Thomas	EDF/SEPTEN, 12-14 Ave Dutrievoz, 69628 Villeurbanne Cedex	France
DELAFOY Christine	Framatome ANP, 10 Rue Juliette Récamier, 69456 Lyon Cedex 06	France
BERNARD Louis-Christian	Framatome-ANP, 10 Rue Juliette Récamier, 69456 Lyon Cedex 06	France
GARNIER Christophe	Framatome-ANP, 10 Rue Juliette Récamier, 69456 Lyon Cedex 06	France
MAILHE Pierre	Framatome-ANP, 10 Rue Juliette Récamier, 69456 Lyon Cedex 06	France
MOREL Etienne	Framatome-ANP, 10 Rue Juliette Récamier, 69456 Lyon Cedex 06	France
VESCO Philippe	Framatome-ANP, 10 Rue Juliette Récamier, 69456 Lyon Cedex 06	France
CAZALIS Bernard	IRSN, DPAM/SEMCA/LEC, BP 3, 13115 SAINT-PAUL-LEZ-DURANCE CEDEX	France
CHARPENEL Jean	IRSN, DPAM/SEMCA/LEC, BP 3, 13115 SAINT-PAUL-LEZ-DURANCE CEDEX	France
DESQUINES Jean	IRSN, DPAM/SEMCA/LEC, BP 3, 13115 SAINT-PAUL-LEZ-DURANCE CEDEX	France
FEDERICI Eric	IRSN, DPAM/SEMCA/LEC, BP 3, 13115 SAINT-PAUL-LEZ-DURANCE CEDEX	France
FRIZONNET Jean-Michel	IRSN, DPAM/SEMCA/LEC, BP 3, 13115 SAINT-PAUL-LEZ-DURANCE CEDEX	France
LEMOINE Francette	IRSN, DPAM/SEMCA/LEC, BP 3, 13115 SAINT-PAUL-LEZ-DURANCE CEDEX	France

MONERIE Yann	IRSN, DPAM/SEMCA/LEC, BP 3, 13115 SAINT-PAUL-LEZ-DURANCE CEDEX	France
PAPIN Joëlle	IRSN, DPAM/SEMCA/LEC, BP 3, 13115 SAINT-PAUL-LEZ-DURANCE CEDEX	France
PETIT Marc	IRSN, DPAM/SEMCA/LEC, BP 3, 13115 SAINT-PAUL-LEZ-DURANCE CEDEX	France
GUICHERET-RETEL Violaine	Laboratoire de Mécanique Appliquée R. Chaléat, 24 Rue de l'Epitaphe, 25000 BESANCON	France
VITANZA Carlo	OCDE/NEA, Le Seine Saint-Germain, 12 Bd des Iles, 92130 ISSY-LES-MOULINEAUX	France
SARTORI Enrico	OECD/NEA, 12 Bd des Iles, 92130 ISSY-LES-MOULINEAUX	France
SONTHEIMER Fritz	Framatome ANP, FGTM, Bunsenstrasse 43, 91058 ERLANGEN	Germany
DEWES Peter	Framatome ANP, Postfach 3220, 91050 ERLANGEN	Germany
LANDSKRON Horst	FRAMATOME-ANP, Bunsenstr. 43, 91058 ERLANGEN	Germany
VAN UFFELEN, Paul	Institute for Transuranium Elements, Herman Von Helmholtz Platz 1, 76344 EGGENSTEIN-LEOPOLDSHAFEN	Germany
WALKER Clive	Institute for Transuranium Elements, Postfach 2340, D-76125 KARLSRUHE	Germany
KOCK Paul	TÜV Hannover/Sachsen-Anhalt e.v., Am TÜV 1, D-30519 HANNOVER	Germany
GRIGER Agnès	Atomic Energy Engineering, Ltd. H-1525 Budapest, P.O. Box 49	Hungary
WIESENACK Wolfgang	Institutt for Energiteknikk, P.O.B 173, N - 1750 Halden	Norway
TVERBERG Terje	OECD Halden Reactor Project, Os Allé, P.O. Box 173, N-1777 Halden	Norway
PARASCHIV Adrienna	Institute for Nuclear Research P.O. Box 78, 0300 PITESTI	Romania
KHVOSTOV Grigori	A.A. Bochvar All-Russian Research Institute of inorganic Materials (VNIINM), Rogova Str. 5a, P.O. Box 369, 123060 MOSCOW	Russia
KORYSTIN Leonid	A.A. Bochvar All-Russian Research Institute of Inorganic Materials (VNIINM), Rogova Str. 5a, P.O. Box 369, 123060 MOSCOW	Russia
BOUROUKINE Andreï	FSUE "SSC of Russia - RIAR", Material Science Division, DIMITROVGRAD 10, Ulyanovsk Region 4333510	Russia
LIKHANSKI Vladimir	SRC RF "TRINITI", 142191 TROITSK, Moscow Region	Russia
POLENOK Vladimir	SSC Institute of Atomic Reactors (RIAR), 433510 DIMITROVGRAD-10, Ulyanovsk Region	Russia
RYU Ho Jin	Korea Atomic Energy Research Institute, Dry Process Fuel, Technology Development Division, 150 Deokjin-dong, Yuseong-gu, DAEJON 305-353	South Korea
KIM Young Min	Korea Atomic Energy Research Institute, LWR Fuel Development Division, P.O. Box 105, Yuseong-gu, DAEJON 305-600	South Korea
KIM Jun Hwan	Korea Atomic Energy Research Institute, Zirconium Fuel Cladding Team, P.O. Box 105, Yuseong-gu, DAEJON 305-600	South Korea
CHEON Jin-Sik	Korea Atomic Energy Research Institute, P.O. Box 105, Yuseong-gu, DAEJON 305-600	South Korea

BARRIO Félix V.	CIEMAT, Avda. Complutense 22, 28040 MADRID	Spain
SERNA Juan J.	Santiago Rusinol 12, ENUSA Industrias Avanzadas SA, 28003 MADRID	Spain
RUDLING Peter	Ekbacken 33, SE-735 35 SURAHAMMAR	Sweden
NORDSTRÖM Eric	Nuclear Design & Analysis, PWR, Vattenfall Bränsle AB, SE-16787 STOCKHOLM	Sweden
LYSELL Gunnar	Studsvik Nuclear AB, Fuel technology, SE-611 82 NYKÖPING	Sweden
ALVAREZ Anna-Maria	Studsvik Nuclear AB, SE-611 82 NYKÖPING	Sweden
LOSIN Carolina	Studsvik Nuclear AB, SE-611 82 NYKÖPING	Sweden
LINDBACK Jan-Erik	Westinghouse Electric Sweden AB, SE-721 63 Vasteras	Sweden
NORDSTRÖM Lars	Paul Scherrer Institute, CH-5232 VILLIGEN PSI	Switzerland
VAN BLOOIS J. Theo	NPP Borssele, Zeedijk 32, 4454 PM BORSELE	The Netherlands
BARKER Matthew	BNFL, B582/2S, Selolafield, Seascale, Cumbria, CA20 1PG	United Kingdom
SHEA John	British Energy, Barnett Way, Barnwood, Goucester, GL4 3RS	United Kingdom
COOK Paul	British Nuclear Fuels, B582/2S SELLAFIELD, Seascale, Cumbria CA20 1PG	United Kingdom
TURNBULL James Anthony	Cherry-Lyn, The Green, Tockington, BRISTOL B S32 4NJ	United Kingdom
HARBOTTLE John	Stoller (UK) Nuclear Fuel Division of NAC International 49 High Street, Thornbury, BRISTOL BS35 2AR	United Kingdom
ARIMESCU Viorel-Ioan	2101 Horn Rapids Road, RICHLAND, WA 99352	USA
RASHID Joseph	ANATECH Corporation, 5435 Oberlin Drive SAN-DIEGO, CA 92121	USA
MONTGOMERY Robert	ANATECH Corporation, SAN-DIEGO, CA 92121	USA
YAGNIK Suresh	EPRI, 3412 Hillview Avenue, Palo Alto, CA 94566	USA
BILLAUX Michel	Framatome ANP, 2101 Horn Rapids Road, RICHLAND, WA 99352	USA
MITCHELL David	Westinghouse Electric Company, 5801 Bluff Road, Columbia, SC 29250	USA